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Key Points:

- Multitemporal HiRISE images show that linear dunes on Mars which nucleate from fixed sources grow by elongation, with no lateral movement
- The linear dunes are elongating at similar rates to the advance rates of barchans and no longer elongate as they approach a steady state
- Martian linear dune growth is comparable to terrestrial systems, demonstrating similarities in dune dynamics across two planetary bodies

Supporting Information:

- Supporting Information S1
- Movie S1
- Movie S2
- Movie S3
- Movie S4
- Movie S5
- Movie S6
- Movie S7
- Movie S8

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Morphology, Development, and Sediment Dynamics of Elongating Linear Dunes on Mars

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Abstract Linear dunes occur on planetary surfaces, including Earth, Mars, and Titan, yet their dynamics are poorly understood. Recent studies of terrestrial linear dunes suggest they migrate by elongation only in supply-limited environments. Here, we investigate elongating linear dunes in the Hellespontus Montes region of Mars which are morphologically similar to terrestrial systems. Multitemporal, high-resolution orbital images show these linear dunes migrate by elongation only and that the fixed sediment source of the dunes probably restricts any lateral migration. Some linear dunes maintain their along-length volume and elongate at rates comparable to adjacent barchans, whereas those which decrease in volume show no elongation, suggesting they are near steady state, matching morphometric predictions. Limited sediment supply may restrict Martian linear dunes to several kilometers, significantly shorter than many terrestrial linear dunes. Our results demonstrate the close similarities in dune dynamics across the two planetary surfaces.

Plain Language Summary Linear dunes are elongated sand ridges found on Earth, Mars, and Titan and form in areas with at least two wind directions. The way in which linear dunes move is poorly understood, in particular whether they migrate parallel or perpendicular to their ridge crests. Recent investigations have suggested that linear dunes on Earth migrate parallel to their ridge crests in areas with a fixed source of limited sand. The surface of Mars is a natural laboratory for investigating linear dunes. We use time series, high-resolution orbital images to investigate the migration of Martian linear dunes. Like those on Earth, the Martian linear dunes also originate from a fixed sand source and grow parallel to their crests only. Furthermore, we also show that the linear dunes no longer grow as they approach a steady state. Our results demonstrate strong similarities in the behavior of dunes on Mars and Earth.

1. Introduction

Aeolian bedforms on planetary surfaces are a record for wind regime, past and current climate, erosion rates, and availability of sediment (e.g., Banham et al., 2018; Bridges et al., 2012; Chojnacki et al., 2019; Day & Catling, 2019; Fenton, 2006). Linear dunes occur on multiple planetary surfaces, including Earth, Mars, and Titan (e.g., Lancaster, 1982; Lorenz et al., 2006; Lucas et al., 2014, 2015; Rubin & Hesp, 2009; Tsoar, 1982, 1989; Tsoar et al., 2004), yet their sediment dynamics are poorly understood. Linear dunes are characterized by elongated sand ridges, whose crests are orientated <15° from the resultant sand flux (transverse dunes are oriented >75° from the resultant sand flux; Hunter et al., 1983; Ping et al., 2014; Figure 1). In terrestrial deserts, linear dunes are often the dominant dune morphology and can extend for tens of kilometers (Bristow et al., 2000; Lancaster, 1995).

Linear dunes develop in multidirectional wind regimes and may migrate laterally (i.e., crest normal; Bristow et al., 2000, 2007; Rubin et al., 2008) and by elongation (i.e., crest parallel; Tsoar, 1989; Lucas et al., 2015). Recent laboratory and numerical experiments demonstrate that in sediment-starved regions (e.g., with nonerodible bedrock), linear dunes develop by elongation at the dune tips, aligned with the mean sediment transport direction (“finger-mode”; Courrech du Pont et al., 2014; Gao et al., 2015; Reffet et al., 2010). This growth mechanism is supported by recent investigations of the Ténéré desert, Niger, where linear dunes develop on the lee of mesas, in an otherwise sand-starved region, and migrate by elongation only, with no lateral migration component (Figure 1a; Lucas et al., 2015). Furthermore, numerical simulations suggest

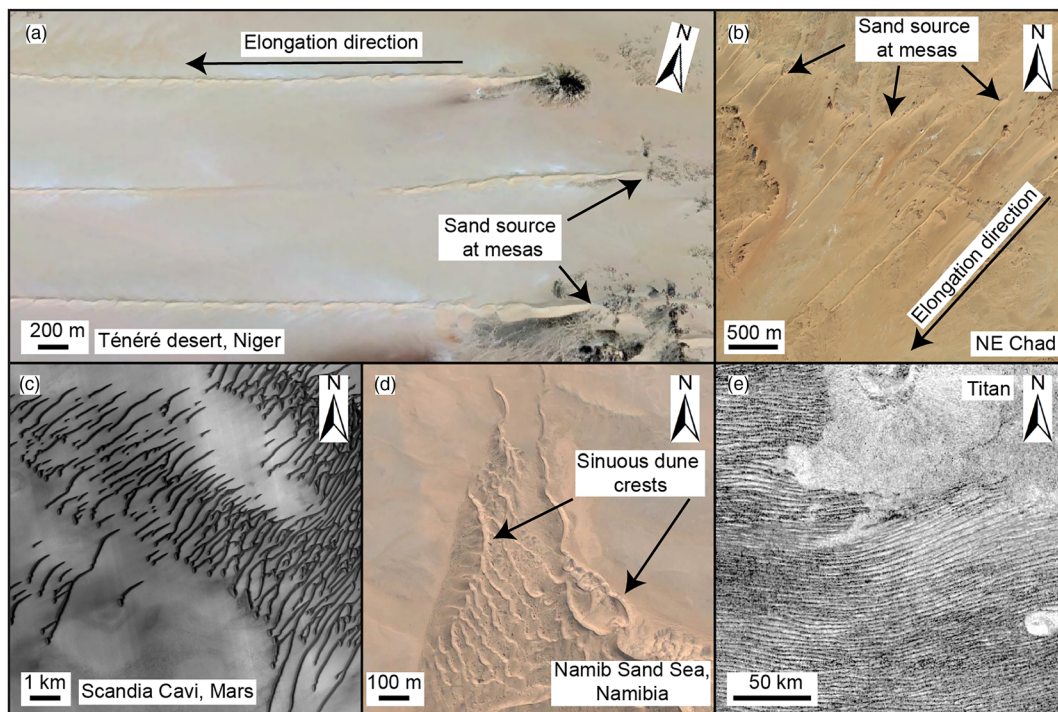


Figure 1. Linear dunes on planetary surfaces. (a) Google Earth/Maxar Technologies image of elongating linear dunes in the Ténéré desert, Niger. (b) ASTER image showing linear dunes in Chad. (c) CTX image showing sinuous linear dunes in the polar Scandia Cavi region, Mars. (d) Google Earth/Maxar Technologies image of sinuous linear dunes in the Namib Sand Sea. (e) Cassini/SAR image showing linear dunes in the equatorial regions of Titan.

that linear dunes elongating from a fixed sediment source take on distinct morphometric characteristics when approaching a steady state, whereby the dunes no longer elongate as the sediment input balances the output (Rozier et al., 2019). Testing these predictions and comparing terrestrial linear dunes to those on other planetary surfaces is critical for understanding dune dynamics, yet there are few studies on planetary linear dunes (other than Titan; e.g., Lucas et al., 2014).

In contrast to Earth and Titan where linear dunes form extensive sand seas, linear dunes in nonpolar regions of Mars are rare, although not absent completely (Hayward et al., 2014). The abundance of high-resolution, multitemporal orbital data means that the surface of Mars is an important laboratory for understanding linear dunes on planetary surfaces. Indeed, active aeolian bedforms are observed across multiple locations on Mars, both from high-resolution orbital images (e.g., Banks et al., 2018; Bridges et al., 2012; Chojnacki et al., 2018; Runyon et al., 2017; Silvestro et al., 2013) and landed spacecraft (e.g., Bridges & Ehlmann, 2018; Sullivan et al., 2008). Here we report on the morphology, development, and sediment dynamics of nonpolar linear dunes on Mars, focusing on a dune field in Hesperontus Montes. Like the Ténéré desert, the Hesperontus linear dunes form on the lee of mesas. The aim of our study is to understand whether the predicted and observed dynamics of terrestrial elongating linear dunes applies to Martian systems.

2. Study Sites

We used the Mars Global Digital Dunes Database (Hayward et al., 2014) to select sites with similar physiographical settings to those where terrestrial elongating linear dunes occur. We chose not to investigate polar linear dunes (Schatz et al., 2006) as the seasonal occurrence of H₂O and CO₂ ice (e.g., Ewing et al., 2010) complicates dune processes. Our main study site is an 8 by 10 km dune field in Hesperontus Montes (41.5°S, 44.5°E) and comprises linear and barchan dunes. The Hesperontus Montes dune field contains some of the best developed linear dunes on Mars and has extensive repeat High Resolution Imaging Science Experiment (HiRISE; 0.25–0.5 m/pixel; McEwen et al., 2007) coverage, spanning 8 Earth years (EY). High regional sediment fluxes are associated with Hellas basin slope winds, midlatitude westerlies,

and locally rugged terrain (Chojnacki et al., 2019). We also investigate four other dune fields which contain linear dunes: Nili Patera (8.7°N, 67.3°E), Meroe Patera (7.6°N, 67.5°E), Capen crater (6.4°N, 13.9°E), and a dune field on the NW margin of the Argyre basin (46.8°S, 54.2°W). Suitable repeat HiRISE images are available for the Nili Patera and Capen crater sites, although only single HiRISE and ConText Camera (CTX; 6 m/pixel; Malin et al., 2007) images are available for the other sites. The Nili Patera and Meroe Patera dune fields are known to be active (e.g., Bridges et al., 2012; Chojnacki et al., 2019).

3. Data and Methods

We used a combination of HiRISE and CTX image and topographic data sets to investigate the Martian linear dunes and obtain morphometric information (length, width, and height). We produced multitemporal HiRISE data sets to quantify linear dune migration rates and sediment fluxes. We used ISIS3 and SOCET SET to produce digital elevation models (DEMs; 1–2 and 20 m/pixel for HiRISE and CTX, respectively; Kirk et al., 2008). The HiRISE DEMs were used to produce precisely coregistered and orthorectified time series images, following established practices (Chojnacki et al., 2018; Davis et al., 2020). We also acquired HiRISE DEMs and coregistered orthorectified images from the HiRISE Planetary Data System node. We then measured the displacement of the linear dune fronts to derive migration rates, as demonstrated by Lucas et al. (2015). The crest height near the linear dune fronts was multiplied by migration rates to produce estimates of dune sand fluxes (Bridges et al., 2012; Chojnacki et al., 2018). A detailed methods description is given in the supporting information.

4. Linear Dunes at Hellespontus Montes

4.1. Morphology and Morphometry of the Hellespontus Montes Linear Dunes

The linear dunes at the Hellespontus Montes site nucleate from sand patches containing meter-scale ripples on the western side of 40–80 m high mesas, present throughout the dune field (Figure 2). The 12 developed linear dunes which originate from the mesas are 1–5 km long and have low sinuosity along their lengths, except where they divert around local topographic obstacles. The heights (~0.5–30 m) and widths (~10–150 m) of individual linear dunes are not constant, and many have aspect ratios (height divided by the half width) that vary along the dune (Figure 3).

The linear dunes can be broadly divided into two categories based on their morphometric data (Figure 3). Type A linear dunes are longer (>1 km) and maintain a similar width and height along their length, or even volumetrically increase, although local undulations do occur (Figures 3b and 3c). In contrast, Type B linear dunes are <1 km in length and decrease in both width and height along the length of the dune (Figure 3b and 3c). Type A and B dunes have differing aspect ratios: While Type A dunes maintain a similar aspect ratio along their length, the aspect ratio for the Type B dunes decreases along their length (Figure 3d). Type B dunes are sometimes found adjacent to the Type A dunes, and where this occurs there are associated bulges in the Type A dunes (local increases in dune volume; Figure 3a), suggesting that sand transfer between dunes is occurring.

Some linear dunes have sharply defined crests with near-symmetric profiles, consistent with sediment deposition occurring on both dune flanks. However, other dunes have a more muted profile with flatter upper surfaces (note crest profiles can vary along dune). In Type B dunes, the top surfaces become more tabular toward the dune tip. Meter-scale dune ripples are found on both the dune flanks with ripple crests perpendicular/oblique to dune crests (Figure 2c). Very few interdune sand deposits are observed throughout the dune field (except around the mesas), consistent with the dune field being a sand-starved region.

At various point along the Type A linear dunes segmentation occurs, forming new bedforms which are no longer attached to the mesas (Figure 2c). Barchan ejection is also observed at the termination of all Type A dunes and some Type B dunes (beginning ~2–5 km from the mesas). The longest linear dune (~5 km) is segmenting into several bedforms (causing localized dune thinning) and, at the distal end of the dune field, ejecting barchans. The barchans extend for ~5 km to the western margins of the dune field. Some of the barchans have extended horns, which may indicate that they are transitioning back into linear dunes. Developed slip faces are generally only observed on linear dunes where new bedforms are breaking away (Figure 2c) and not along the lateral margins of the dunes.

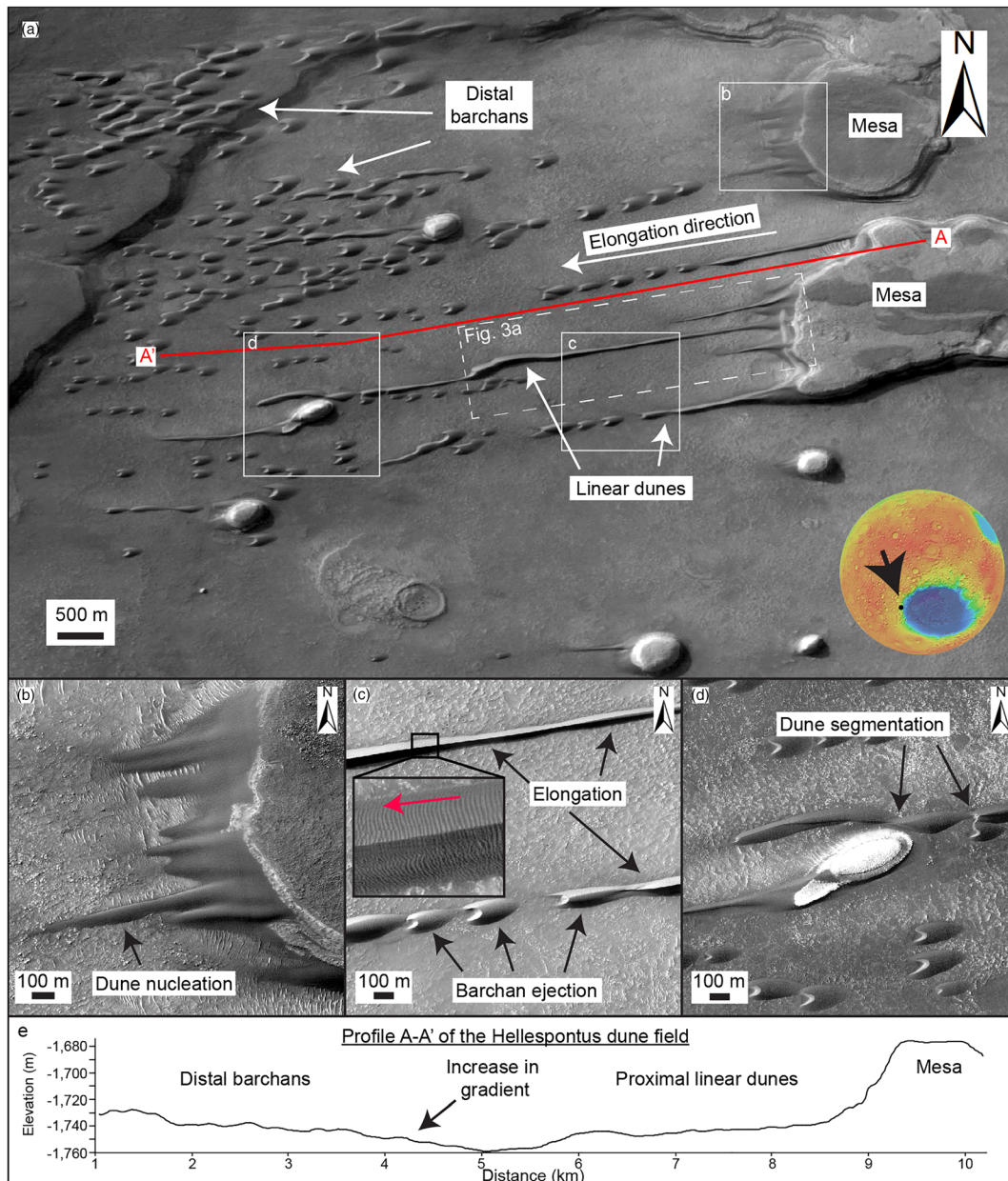


Figure 2. (a) CTX image showing elongating linear and distal barchan dunes at Hesperosaurus Montes. (b) HiRISE image showing linear dunes nucleating from sand patches on the lee of mesas. (c) HiRISE image showing linear dunes elongating westward and ejecting barchan dunes. Note the lack of interdune sand. Inset shows meter-scale dune ripples and inferred migration direction. (d) HiRISE image showing linear dune segmentation into several bedforms as it diverts around a mesa. (e) CTX DEM topographic profile along the dune field.

4.2. Migration Patterns and Sediment Fluxes of Hesperosaurus Linear Dunes

Both the linear and barchan dunes at Hesperosaurus are migrating westwards. We also observed displacement of the meter-scale ripples on the linear dunes. The displacement measurements show the Type A linear dunes are elongating at a mean rate of 1.3 ± 0.2 m/EY, along their length (Movies S1–S3), giving mean crest sediment fluxes of 28.1 ± 2.2 m³ m^{−1} EY^{−1}. All our measurements are from the proximal section of the dune field (Figure S1); however, they are similar to the distal barchan dune advance rates (0.9 m/EY; 16.8 m³ m^{−1} EY^{−1}; Chojnacki et al., 2019). In contrast, for Type B linear dunes, we observed very little migration over 8 EY, although westward ripple displacement suggests sand on these dunes is still mobile (Movies S4 and S5). Importantly, we did not observe significant lateral migration along the length of any of the linear dunes.

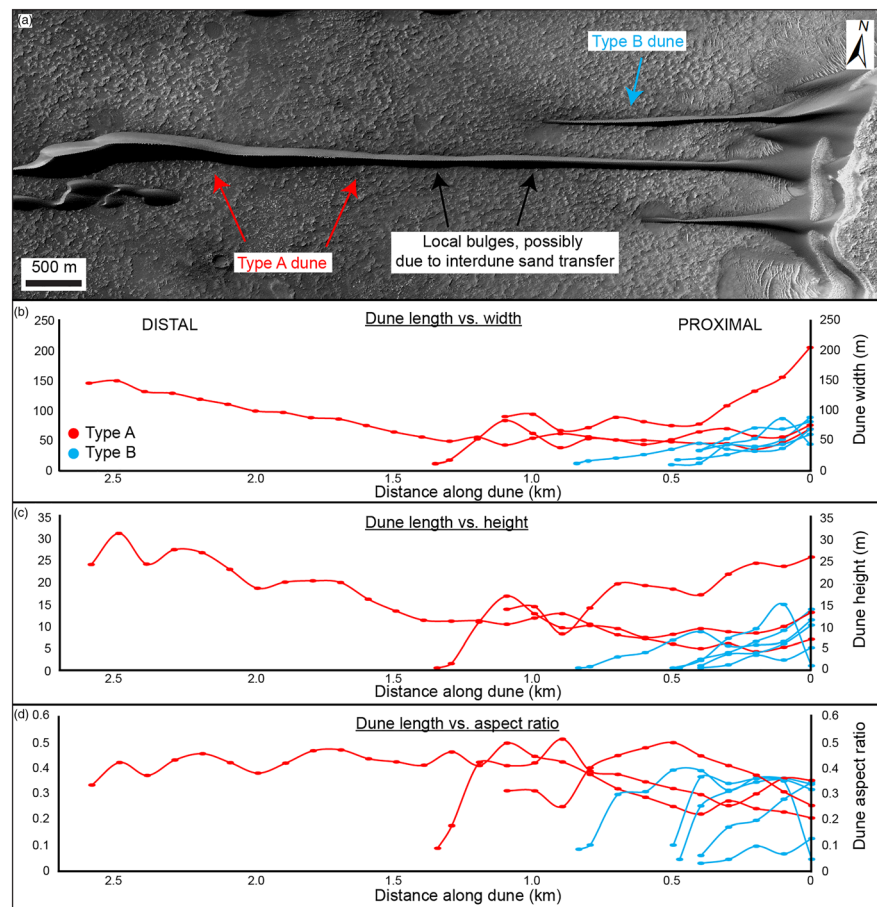


Figure 3. Morphometry of Hellespontus linear dunes. (a) HiRISE image of example Type A and B linear dunes at Hellespontus Montes. (b–d) Morphometrics for all measured Type A and B linear dunes, showing (b) width, (c) height, and (d) aspect ratio changes with dune length. Type A dunes are >1 km and maintain similar widths, heights, and aspect ratios along their length, whereas Type B dunes are <1 km and decrease in width, height, and aspect ratio along their lengths.

4.3. Development of Elongating Linear Dunes at Hellespontus Montes

The observed lengthways migration direction suggests that the linear dunes are migrating by elongation (i.e., crest parallel) only, which is supported by the (1) lack of meandering waveform along the dune; (2) the orientation of the ripple crests (suggesting migration along the dune); (3) and the fixed sand source of the dunes (Courrech du Pont et al., 2014; Lucas et al., 2015; Reffet et al., 2010; Rozier et al., 2019).

The occurrence of elongating Type A linear dunes, which maintain a similar volume (or even increase) along their lengths, and the static Type B linear dunes, which decrease in volume along their lengths, in the same dune field is particularly interesting. Recent numerical simulations by Rozier et al. (2019) suggest that these morphometrics are related to the maturity of the linear dunes. The length and volume of the linear dunes are predicted to be a function of sediment input, which reaches a maximum value with time as longer dunes have more area to lose sediment from (Rozier et al., 2019). The observed elongation of the Type A linear dunes suggest they have not yet reached their maximum length.

In contrast, steady-state linear dunes will no longer elongate (having reached their maximum length), as the input sand flux equals the output sand flux, and consequently the dune volume decreases along their length (Rozier et al., 2019). The decreasing volume of the Type B linear dunes and their lack of observed elongation at Hellespontus over 8 EY suggests they may be at or near steady state. The Rozier et al. (2019) simulations also predict interdune sand transfer between adjacent linear dunes, which is inferred at Hellespontus (Figure 3a). The largest linear dune at Hellespontus is flanked by two smaller (Type B) linear dunes, which may be supplying the larger dune with an additional source of sand (Figure 3a).

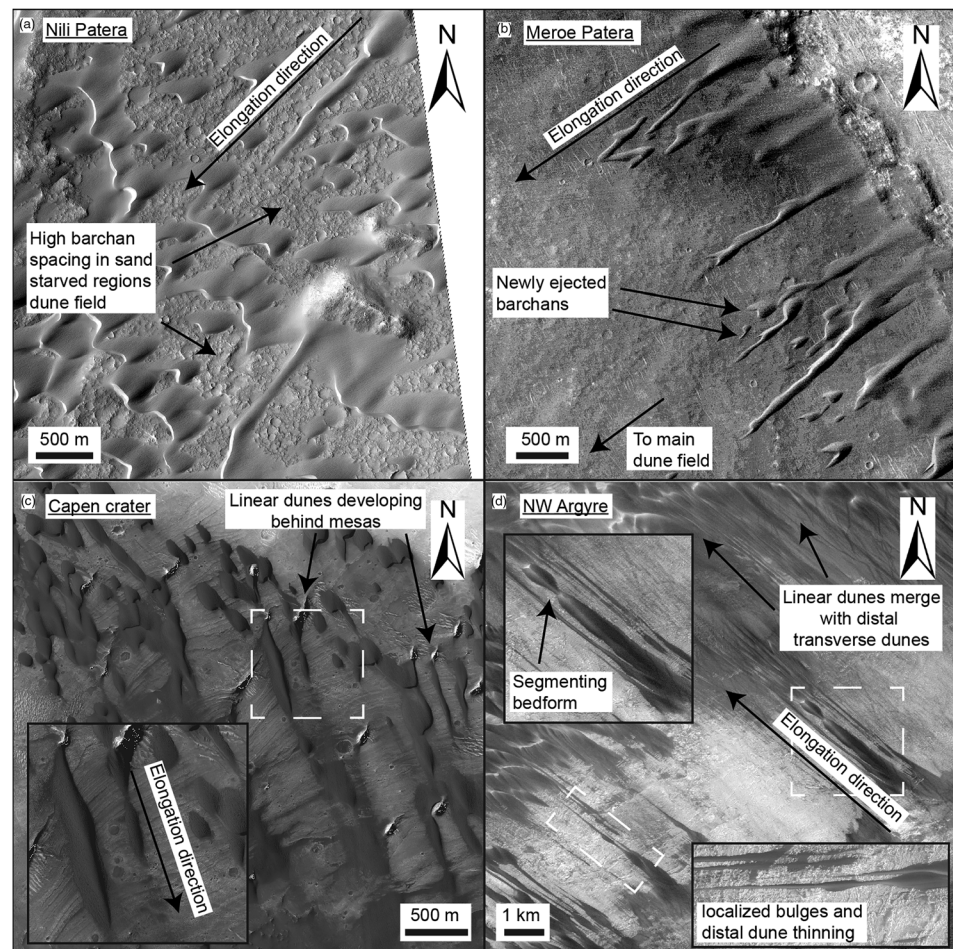


Figure 4. Examples of elongating linear dunes on Mars. (a) HiRISE image showing elongating linear dunes in sand-starved parts of the Nili Patera dune field. (b) CTX image of elongating linear dunes near the Meroe Patera dune field. Like at Hesperontus, barchan ejection and segmentation of new bedforms is observed. (c) HiRISE image showing Capen crater dune field, where barchans trend into elongating linear dunes. (d) CTX image (HiRISE sub-panel; bottom right) showing elongating linear dunes in the NW Argyre region. In all examples, these linear dunes elongate from the lee of obstacles.

5. Elongating Linear Dunes Elsewhere on Mars

Elongating linear dunes in other regions of Mars show similar trends to those at Hesperontus Montes (Figure 4). At Nili and Meroe Patera, linear dunes are present at the margins and in other sand-starved regions of the dune fields. The Nili and Meroe linear dunes elongate from the lee of local mesas or regional scarps. At Nili Patera, the linear dunes sometimes merge with barchan or barchanoid dunes (Figure 4a), whereas at Meroe Patera, barchans are ejected at the distal end of the linear dunes, or the dunes segment to form new bedforms (Figure 4b). At both sites, the dunes mostly maintain similar volumes along their lengths, and significant lengthways thinning is not observed. The Nili Patera linear dunes are elongating at their tips at a rate of 0.75 ± 0.1 m/EY (sediment flux: 8.2 ± 0.9 m³ m⁻¹ EY⁻¹; Movie S6), similar to the advance rate of nearby barchans (0.77 ± 0.2 m/EY; Chojnacki et al., 2019). No multitemporal HiRISE images were available for Meroe Patera, although nearby barchan activity suggests the linear dunes are likely active and their morphology is consistent with ongoing elongation.

Linear dunes are also found at the south of Capen crater (Figure 4c), where barchans trend into linear dunes, elongating from both sand which has accumulated behind mesas and the extended horns of barchans. Like Nili and Meroe, the linear dunes maintain similar volumes along their lengths, although they are poorly defined compared to the other sites. The Capen crater linear dunes are elongating at 0.36 ± 0.2 m/EY

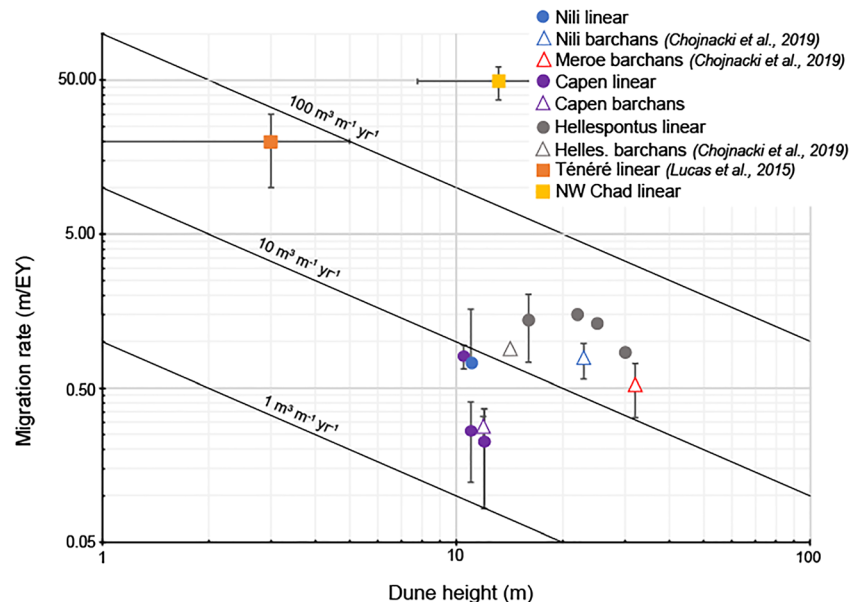


Figure 5. Log log plot showing the dune height versus migration rates for Martian linear dunes in this study (circles), nearby barchans (triangles), and select terrestrial linear dunes (circles). The linear dunes are elongating at similar rates to migrating barchans.

(crest flux: $4 \pm 1.9 \text{ m}^3 \text{ m}^{-1} \text{ EY}^{-1}$; Movie S7), similar to barchan advance rates ($0.26 \pm 0.1 \text{ m/EY}$; $3.1 \pm 0.7 \text{ m}^3 \text{ m}^{-1} \text{ EY}^{-1}$). The NW Argyre dune field (Figure 4d) contains linear dunes (elongating from behind mesas) which transition into transverse dunes and an eventual sand sea. Like Hellespontus, this site contains dunes that both maintain a similar volume (Type A) and decrease in volume lengthways (Type B). Although no multitemporal images are available for this site, both partially and fully ejected barchans suggest that some of the linear dunes here are active, whereas others may no longer be actively elongating. At all sites, the linear dunes do not exceed $\sim 3 \text{ km}$ in length and show little evidence for lateral migration.

6. Age of the Linear Dunes

As the active linear dunes are elongating from a fixed source, their approximate age should be proportional to their lengths. Assuming a constant elongation rate, the longest linear dune ($\sim 5 \text{ km}$) at Hellespontus Montes began forming $\sim 3,800 \text{ EY}$ ago. Similarly, the actively elongating dunes at Nili Patera and Capen crater should be $\sim 1,300$ and $2,800 \text{ EY}$ old, respectively. Our measurements at Hellespontus, Nili Patera, and Capen crater indicate linear dunes are elongating at similar rates to the advance rate of barchans (Figure 5). Assuming a similar advance rate to the nearby barchans (Chojnacki et al., 2019), the Meroe Patera linear dunes should be $\sim 5,000 \text{ EY}$ old. The migration rates for these sites were all measured across multiple Mars years (MY): Hellespontus, MY 29–33; Nili, MY 28–30; Capen, MY 30–32; and Meroe, MY 29–32. These ages all suggest that the linear dunes are geologically recent features.

7. Comparison to Terrestrial Linear Dunes

The morphology and migration patterns of the Martian linear dunes share a number of similarities to terrestrial elongating linear dunes (e.g., Ténéré desert, Niger; NE Chad; Movie S8), both from field and remote observations (e.g., Lucas et al., 2015) and predicted by laboratory experiments and numerical modeling (Courrech du Pont et al., 2014; Gao et al., 2015; Reffet et al., 2010; Rozier et al., 2019). Few interdune sand deposits are observed in the Martian dune fields, consistent with the linear dunes forming in a sediment limited environment, possibly on nonerodible bedrock (Courrech du Pont et al., 2014; Reffet et al., 2010). As in terrestrial examples, the fixed and limited sand source for the linear dunes (the mesas) appears to be restricting their ability to laterally migrate, causing them to grow by elongation only, as predicted by modeling and observed in the field (Courrech du Pont et al., 2014; Lucas et al., 2015; Reffet et al., 2010), as they approach a

steady state (Rozier et al., 2019). On Titan, dune morphology, exposed interdune substrate, and climate models suggest that the equatorial linear dunes also grow by elongation, with limited sediment availability (e.g., Lorenz et al., 2006; Lucas et al., 2014). Like terrestrial elongating dunes, the Martian dunes generally have higher aspect ratios (~ 0.2 – 0.4) than sinuous linear dunes which laterally migrate (~ 0.15 ; Bristow et al., 2007; Rubin & Hesp, 2009). Additionally, linear dune segmentation and barchan ejection are all observed in terrestrial deserts where elongating linear dunes are found (Lucas et al., 2015).

We also note some significant differences from terrestrial linear dunes. Currently, linear dunes are rare on Mars outside of the polar regions (Hayward et al., 2014), and very few individual linear dunes occur within the sites we examined (Hellespontus had the most, 12). Most of the Martian linear dunes did not exceed 1–3 km in length, whereas terrestrial linear dunes in parts of the Sahara (Figure 1; Lucas et al., 2015) are often kilometers to tens of kilometers long (although the dunes are similar in height; Figure 5). On Titan, linear dunes can extend for more than a hundred kilometers in length (e.g., Lorenz et al., 2006). This length difference could be explained by limited sediment availability at all the sites (Rozier et al., 2019), or alternatively, the multidirectional winds forming the linear dunes could be a local phenomenon caused by unidirectional winds diverting around the source mesas (as opposed to regional, multidirectional winds). Nevertheless, although elongating Martian linear dunes are comparatively rare, the morphology and observed migration patterns of the dunes suggest strong similarities in dune dynamics between Mars and Earth. Finally, we stress that our observations and sand fluxes of active linear dunes are from a small sample size (~ 10) due to the limited availability of multitemporal HiRISE images. Additional images of Martian linear dunes will improve this spatial and temporal coverage.

8. Conclusions

Our observations show that the linear dunes at Hellespontus Montes elongate from a fixed and limited sediment source, at rates comparable to the advance rate of nearby barchans, with little to no lateral migration. Those linear dunes which are actively elongating maintain their volume along their length, whereas those dunes which decrease in volume were not observed to elongate and may have reached a steady state. Sand transfer may occur between dunes, where sand from dunes in a steady state supply sand to adjacent, elongating dunes. As in terrestrial and other Martian examples, the fixed, limited sand source appears to prevent lateral dune migration. Dune elongation rates suggests the linear dunes are $\sim 10^3$ EY old. These observations are consistent with terrestrial elongating linear dunes and predictions from numerical models and laboratory experiments, demonstrating a convergence in dune dynamics between the two planetary bodies. Additional HiRISE and CTX images will expand both spatial and temporal coverage of Martian linear dunes and improve our understanding of dune dynamics.

Data Availability Statement

The standard data products used here are available from the NASA PDS (<https://pds.jpl.nasa.gov/>). The HiRISE and CTX DEMs and co-registered time series images are available for download at <https://doi.org/10.6084/m9.figshare.c.4932006.v1>

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